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The Luminosity of SN 1999by in NGC 2841 and the Nature of the "Peculiar" Type Ia Supernovae

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ABSTRACT

We present $UBVRIJHK$ photometry and optical spectroscopy of the so-called "peculiar" Type Ia supernova 1999by in NGC 2841. The observations began one week before visual maximum light which is well-defined by daily observations. The light curves and spectra are similar to those of the prototypical subluminous event SN 1991bg. We find that maximum light in B occurred on 1999 May 10.3 UT (JD 2,451,308.8±0.3) with $B = 13.66 \pm 0.02$ and a color of $B_{max} - V_{max} = 0.51 \pm 0.03$. The late-time color implies minimal dust extinction from the host galaxy. Our photometry, when combined with the recent Cepheid distance to NGC 2841 (Macri et al. 2001), gives a peak absolute magnitude

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of $M_B = -17.15 \pm 0.23$, making SN 1999by one of the least luminous Type Ia events ever observed. We estimate a decline rate parameter of $\Delta m_{15}(B) = 1.90$ mag, versus 1.93 for SN 1991bg, where 1.10 is typical for so-called "normal" events. We compare SN 1999by with other subluminous events and find that the $B_{max} - V_{max}$ color correlates strongly with the decline rate and may be a more sensitive indicator of luminosity than the fading rate for these objects. We find a good correlation between luminosity and the depth of the spectral feature at 580 nm, which *had* been attributed solely to Si II. We show that in cooler photospheres the 580 nm feature is dominated by Ti II, which provides a simple physical explanation for the correlation. Using only subluminous Type Ia supernovae we derive a Hubble parameter of $H_0 = 75^{+12}_{-11}$ km s^{-1} Mpc^{-1}, consistent with values found from brighter events.

Subject headings: supernovae: general—supernovae: individual (SN 1957A, SN 1991bg, SN 1998bp, SN1999by)

1. Introduction

Type Ia supernovae (SNe Ia) are good distance indicators because they are intrinsically bright and appear to have a relatively small dispersion in maximum brightness. Phillips (1993) showed that a relation between the peak brightness and light curve decline rate improves their utility as distance indicators. This was exploited by Hamuy et al. (1996a), Riess, Press, & Kirshner (1995) and Jha et al. (1999) to measure the Hubble constant. Much more distant SNe Ia have been used to determine the content of the universe (Garnavich et al. 1998; Schmidt et al. 1998; Riess et al. 1998, Perlmutter et al. 1999).

SNe Ia are fairly homogeneous in spectral characteristics and intrinsic color at maximum (Filippenko 1997), but in 1991 two spectroscopically "peculiar" SNe Ia were discovered (Branch, Fisher, & Nugent 1993). Near maximum light, SN 1991T showed only a weak Si II 615 nm line which is normally the strongest feature in the optical band (Phillips et al. 1992; Filippenko et al. 1992a). It also displayed a very slow light curve evolution compared to more typical events and was thought to be more luminous than average. That same year SN 1991bg showed an extremely fast light curve evolution as well as a red color at maximum light and strong Ti II in its spectrum (Filippenko et al. 1992b; Leibundgut et al. 1993). The maximum brightness of SN 1991bg was also estimated to be two magnitudes fainter than normal events. SN 1986G (Phillips et al. 1987) appears to have properties between normal and the extreme case of SN 1991bg. Nugent et al. (1995) showed that the gross spectral variations among all SNe Ia can be accounted for by simply varying the photospheric temperature, which suggests

peculiar events are just extreme tails of a continuous distribution.

Since 1991, many more supernovae have been discovered serendipitously and in systematic searches, and a handful of supernovae similar to SN 1991T and SN 1991bg have been found and studied. Li et al. (2001) added SN 1999aa as a peculiar sub-class which is similar to SN 1991T well before maximum light, but with significant Ca II absorption not seen in the original. From a volume-limited sample, they find 36 percent of SNe Ia are somehow spectroscopically peculiar, although Branch (2001) points out a selection bias that raises the fraction to 45 percent and casts doubt on the usefulness of the term "peculiar".

Only 16 percent of all the supernovae in the Li et al. sample were classified as SN 1991bg-like with evidence of Ti II in their spectra. Few such peculiar SNe Ia have been studied in detail: 1992K (Hamuy et al. 1994), 1997cn (Turatto et al. 1998), 1998de (Modjaz et al. 2001), and 1999da (Krisciunas et al. 2001). Because of their rapid evolution, they are often discovered after maximum brightness. Even rarer are SNe Ia that bridge the gap between so-called "normal" events and the extreme SN1991bg-like explosions. SN 1986G (Phillips et al. 1987) is one of these intermediate events, but was highly reddened by dust in its host galaxy. More recently, SN 1998bp (Jha et al. 1998; Jha 2002) and SN 2000bk (Krisciunas et al. 2001) appear to fall between the normal and extreme objects.

SN 1999by is another rare example of a "peculiar", fast-declining SN Ia. It was discovered independently by R. Arbour, South Wonston, Hampshire, England, and by the Lick Observatory Supernova Search (LOSS) on 1999 April 30 (Papenkova et al. 1999). SN 1999by is located in NGC 2841, an Sb galaxy, that has been host to three other supernovae (SN 1912A, SN 1957A, and SN 1972R). An early spectrum by Gerardy & Fesen (1999) showed that SN 1999by was a Type Ia event, and Garnavich et al. (1999) found line ratios and Ti II absorption consistent with a SN 1991bg-like supernovae. SN 1999by is also one of the few SNe Ia to show significant intrinsic polarization (Howell et al. 2001; see also Wang et al. 2003 regarding the case of SN 2001el).

Here, we present detailed photometric and spectroscopic observations of SN 1999by. In addition to SN 1999by being fascinating as an unusual supernova, Hubble Space Telescope (*HST*) has studied Cepheid variables in its host galaxy (Macri et al. 2001), which makes SN 1999by useful for defining the distance scale.

2. Observations

2.1. Photometry

Optical broad band photometry of SN 1999by began six days after discovery with the 1.2-m telescope at the Fred L. Whipple Observatory (FLWO). Twenty sets of $UBVRI$ images were obtained between 1999 May 6 and June 21 (UT) using the 4-Shooter camera, which consists of four 2048×2048 CCD chips. Images were taken in a 2x2 binning mode with the supernova centered on chip 3. The image scale was $0.64''$ pixel^{-1}. Late time $UBVRI$ images were obtained at FLWO in 1999 November and December.

The images were bias corrected and flat fielded using the CCD reduction package in IRAF[8]. We used the DAOPHOT package in IRAF to obtain instrumental magnitudes of the supernova and 10 local standard stars using aperture photometry. Tests using point-spread-function (PSF) fitting photometry showed no significant difference between the derived magnitudes. SN 1999by appeared about $3'$ from the center of NGC 2841 where there is still significant light contributed by the disk. However, the galaxy is relatively smooth at the resolution of FLWO with only a mild light gradient at the supernova, permitting an accurate local background to be estimated from an annulus around the star. At late times, no contamination from faint stellar sources is seen at the position of the supernova.

Local standard stars were calibrated on four photometric nights at FLWO and two photometric nights at the Vatican Advanced Technology Telescope (VATT). On all those nights Landolt standard stars (Landolt 1992) were observed over a range of airmasses allowing for the derivation of linear extinction and color coefficients. The standard magnitudes derived for the local calibrators are given in Table 1 corresponding to the stars marked in the finder chart given in Figure 1. For local calibrators observed on multiple nights, the root-mean-square (rms) scatter was 0.03 mag.[9] The supernova instrumental magnitudes from May and June were converted to standard magnitudes using local standards stars 1 to 4. The resulting $UBVRI$ photometry is provided in Table 2 and displayed in Figure 2. Our standard star calibration has substantially improved over that used by Bonanos et al. (1999) which was based on a single non-photometric night, and our V maximum is now consistent with that

[8]Image Reduction and Analysis Facility, distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[9]For secondary standards we prefer to present the mean magnitudes to a resolution of 0.001 mag. In our experience secondary standards have uncertainties of several thousandths of a magnitude to a few hundredths, depending on the filter.

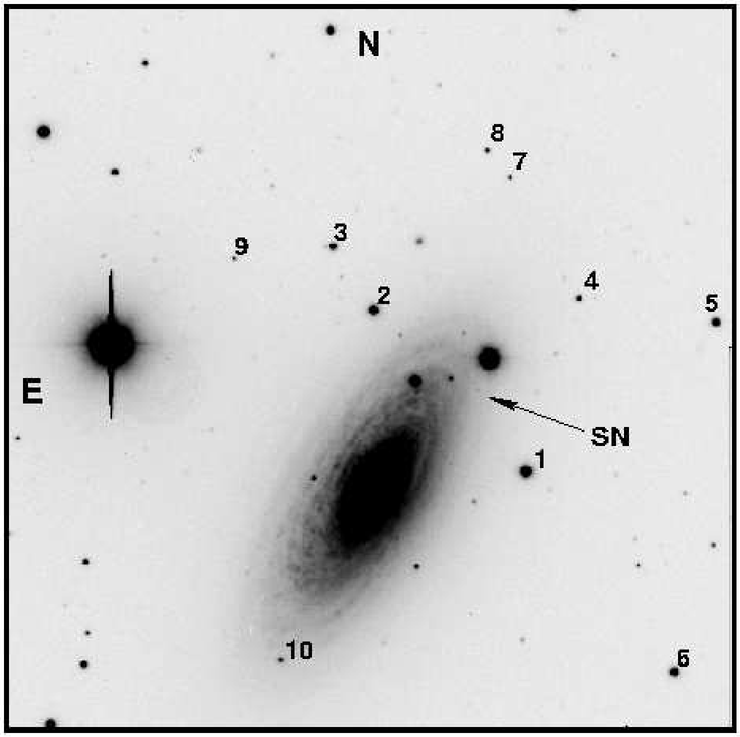

Fig. 1.— The field around NGC 2841 with local comparison stars marked. The field of view is 10.9 by 10.9 arcminutes. The image was taken in 1999 December well after the supernova maximum. The supernova location was at the tip of the arrow.

found by Toth & Szabó (2000).

The optical light curves of SN 1999by shown in Figure 2 are similar to those of the peculiar Type Ia SN 1991bg in their rate of rise and decline from maximum. Although our coverage 10 to 30 days after B_{max} is poor, the SN 1999by light curves in the R and I bands are consistent with those of SN 1991bg, which lacked the prominent secondary maximum seen in Type Ia SNe of mid-range decline rates.

From the highest quality image we derive an accurate position for the supernova of α = 9:21:52.07, δ = 51° 00′ 06.54″ (2000) based on the *HST* Guide Star Catalog coordinates. Using 14 stars in the field of NGC 2841 for the plate solution we get a scatter of 0.2″ (rms) which represents the expected accuracy of the astrometry. This is consistent with the position given by the discoverers (Papenkova et al. 1999).

In Table 3 we give near infrared (IR) data obtained with the FLWO 1.2-m telescope using STELIRCAM, an imaging instrument containing two InSb arrays of 256 × 256 pixels which allows simultaneous blue channel (e.g. J-band) and red channel (e.g. H- or K-band) data acquisition. Data were taken at a resolution of 1.2 ″ pixel^{-1}. On photometric nights

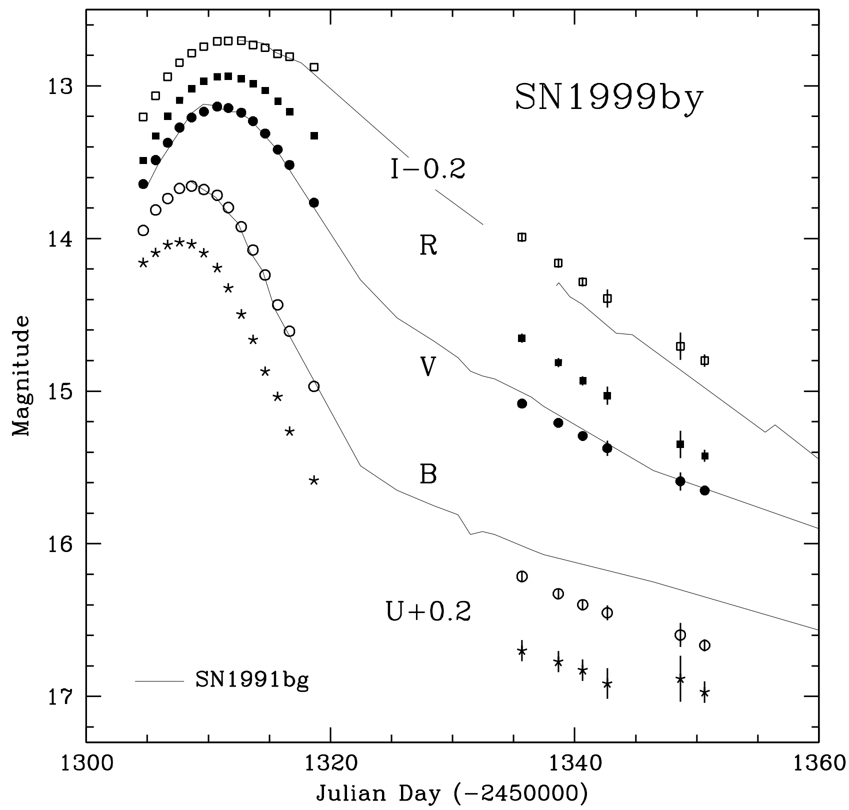

Fig. 2.— Light curves of SN 1999by in the U, B, V, R and I filters. The solid lines show the light curves of SN 1991bg from Leibundgut et al. (1993), with the curves shifted in magnitude and time to match the light curves of SN 1999by at maximum. For the data near maximum, the uncertainties of the photometry are on the order of the size of the points.

bright infrared standards of Elias et al. (1982) or fainter standards of Persson et al. (1998) were observed. From four photometric nights we find $J = 12.100 \pm 0.013$, $H = 11.732 \pm 0.054$, and $K = 11.727 \pm 0.033$ for field star number 1. These values are to be compared with $J = 12.099 \pm 0.028$, $H = 11.728 \pm 0.029$, and $K = 11.632 \pm 0.027$ from the Two Micron All Sky Survey (2MASS). Thus, there is excellent agreement of the IR zeropoints in J and H, but a significant difference of 0.1 mag between our K-band photometry and the 2MASS value for field star number 1. Krisciunas et al. (2004b) has found an offset and scatter between the 2MASS K-band magnitudes and the same stars calibrated with Persson et al. (1998) standards which can account for this inconsistency. In Figure 3 we show our JHK photometry of SN 1999by along with three nights of data given by Höflich et al. (2002).

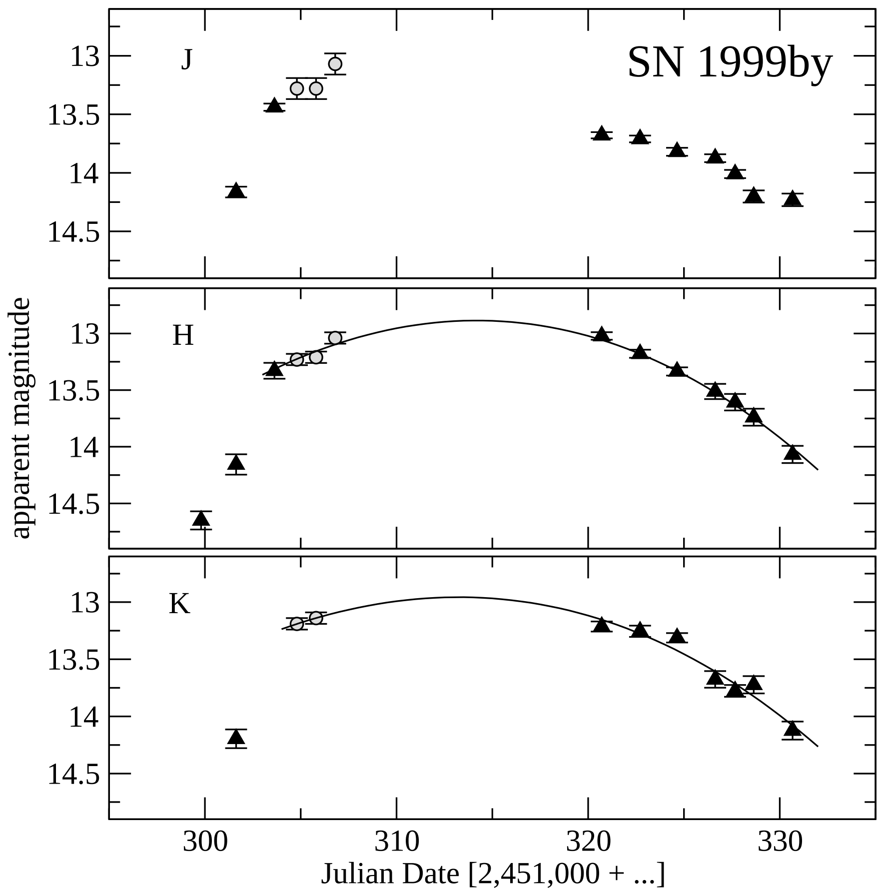

Fig. 3.— JHK light curves of SN 1999by. The open circles are data from Höflich et al. (2002), while the triangles are data from the FLWO 1.2-m telescope given in Table 3. The solid lines show a polynomial fit to the points to aid in estimating the position of maximum light.

2.2. Spectroscopy

Spectroscopic observations of SN 1999by were made using the FLWO 1.5-m telescope with the FAST spectrograph using a 300 line mm^{-1} grating and a 3$''$ wide slit (Fabricant et al. 1998). A majority of the spectra were taken with a single grating setting covering 362 nm to 754 nm. On two nights the observations were done at two grating tilts providing wavelength coverage from 327 nm to just over 900 nm and three spectra were obtained with a 600 line mm^{-1} grating giving twice the resolution but half the typical coverage. Interference fringes were a severe problem at wavelengths longer than 780 nm and could not be completely removed from the data. A total of 18 spectroscopic observations was made between 1999 May 6 and June 22 UT. A log of the observations is given in Table 4.

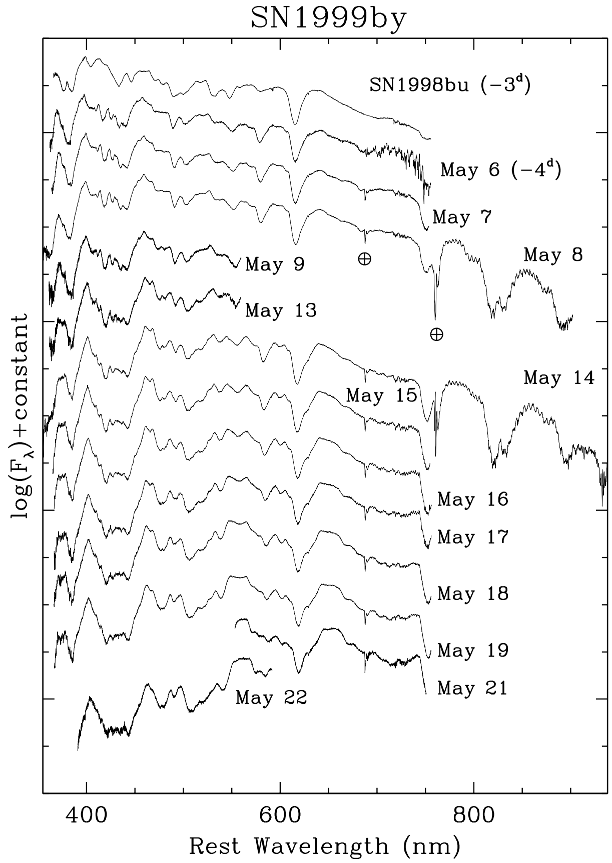

Fig. 4.— Spectra of SN 1999by in May, 1999 from the FLWO 1.5m telescope. For comparison we show the normal but dust reddened SN1998bu three days before maximum light.

We reduced the spectra using IRAF. The two dimensional CCD exposures were bias and dark corrected and then flat fielded. Using the APEXTRACT package, we extracted the 1D spectrum at the supernova position, subtracting the sky estimated along two strips parallel to the spectrum. The supernova signal was strong enough that it was used to trace the centroid along the dispersion. Exposures of a HeNeAr lamp taken after each supernova observation were used to calibrate the wavelength. Flux calibration was done by using the exposures of spectroscopic standard stars taken during the night. The spectrograph slit was set at the parallactic angle for both the supernova and the standard star observations to reduce differential slit losses. Not all the observations were made under photometric conditions. Finally, the data were corrected for the Doppler shift due to the radial velocity

of NGC 2841 (638 km s^{-1}).[10] The reduced spectra are shown in Figures 4 and 5.

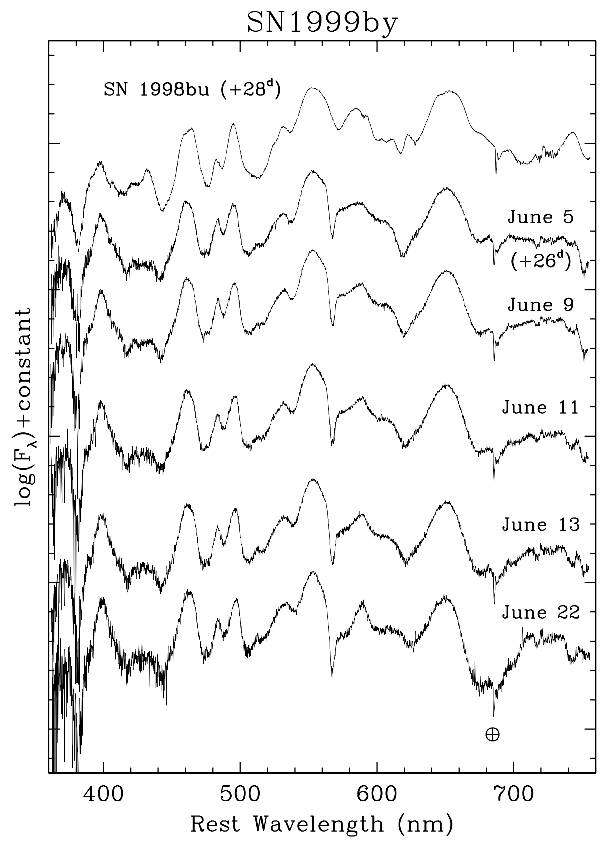

Fig. 5.— Spectra of SN 1999by in June, 1999 during the early nebular stage. For comparison, the top spectrum is that of SN 1998bu at an age of +28 days after B_{max}. The narrow absorption feature seen in SN 1999by near 570 nm is identified as Na I.

3. Discussion

3.1. The Light Curve

The date and magnitude of maximum light in all the filters were estimated by fitting second and third degree polynomials to the May data. Because of the daily sampling, the

[10]This is the heliocentric radial velocity of the host galaxy from the NASA/IPAC Extragalactic Database (NED). As noted by Vinkó et al. (2001), the radial velocity of SN 1999by would contain a 300 km s^{-1}uncertainty due to the rotation of the host galaxy.

$UBVRI$ curves are very well defined and the scatter about the fits was 0.01 mag or less. The results are given in Table 5. A two day difference between the times of B and V maximum (T(B_{max}) and T(V_{max}) is typical of SNe Ia (Leibundgut 1988) and appears from SN 1999by to be true for fast-declining events as well. The Galactic latitude of NGC 2841 is +44° which means that the extinction through our galaxy is low but not necessarily insignificant. The reddening estimate from Schlegel, Finkbeiner, & Davis (1998) is E($B-V$) = 0.016 mag, and this correction has been applied to the maximum magnitudes given in Table 6 assuming the standard Cardelli et al. (1989) extinction law.

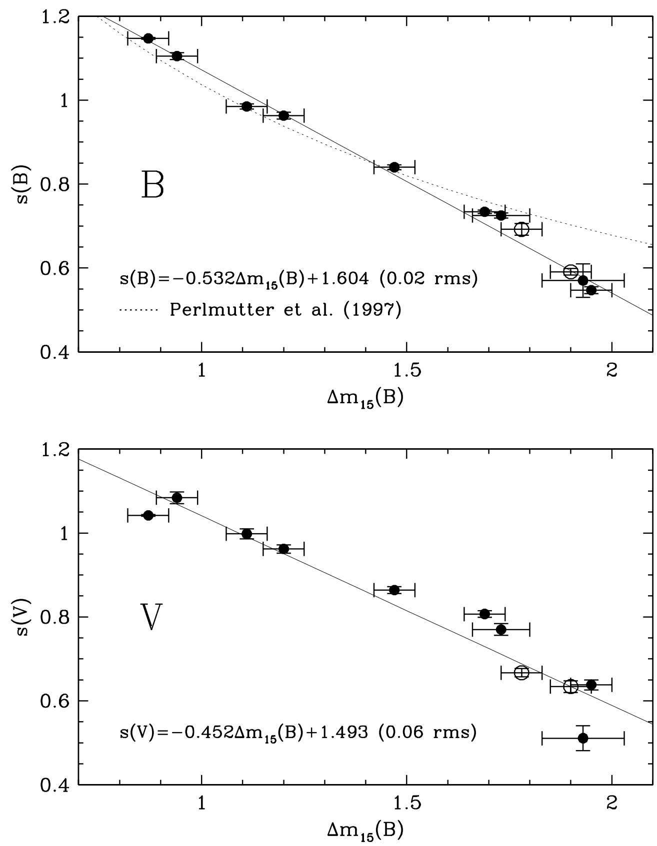

Fig. 6.— The relationship between the stretch parameter, s, and $\Delta m_{15}(B)$. The solid points show the $\Delta m_{15}(B)$ standard SNe Ia from Hamuy et al. (1996) plus SN 1998de from Modjaz et al. (2001). The open points show SN 1998bp and the position of SN 1999by for its measured stretch. The solid line is the best fit line through the solid points. The dotted line is the conversion of a stretch parameter to $\Delta m_{15}(B)$ from Perlmutter et al. (1997) where the light curve templates were restricted to $\Delta m_{15}(B) < 1.75$.

The number of magnitudes a supernova fades during the 15 days after maximum brightness, $\Delta m_{15}(B)$, is a popular way to parameterize a light curve shape. Directly measuring this parameter is difficult from our data because of the lunar gap starting ten days after B_{max}. It is also unwise to use the standard template-fitting technique when there are no known SNe Ia significantly faster than SN 1991bg. Instead, we apply a light curve "stretch method" developed for high-redshift supernovae by Perlmutter et al. (1997). In our implementation, the time axis of the Leibundgut templates (Leibundgut 1988), restricted to $-5 <$ days < 15, are multiplied by a parameter, s, which compresses or expands the template light curve in the time domain, mimicking the variation in decline rate. A χ^2 minimization is applied to an observed light curve after correcting for time dilation, where the stretch factor, time of maximum and magnitude of maximum are free parameters. We then applied this technique to the $\Delta m_{15}(B)$ standard templates defined by Hamuy et al. (1996a) as a way to calibrate the stretch factor against $\Delta m_{15}(B)$. Because we are interested in the fast-declining end of the distribution, we added the well-observed event SN 1998de with $\Delta m_{15}(B) = 1.95 \pm 0.05$ (Modjaz et al. 2001) as a standard light curve.

The calibration between the stretch parameters for B and V and $\Delta m_{15}(B)$ are shown in Figure 6. The conversion of stretch to $\Delta m_{15}(B)$ works best for the B-band with a scatter of only 0.04 mag in $\Delta m_{15}(B)$. Stretch applied to the V-band gives a larger scatter, but consistent results. Direct measurement of the $\Delta m_{15}(B)$ parameter should become slightly non-linear for these very fast-declining events since the first inflection point in the light curve, which signals the onset of the nebular phase, shifts to within 15 days of B_{max}. This likely contributes to the scatter in Figure 6 but does not have a large effect on our goal of estimating $\Delta m_{15}(B)$ for SN 1999by.

We estimate SN 1999by to have $\Delta m_{15}(B) = 1.90 \pm 0.05$ mag, making it a slightly slower declining light curve relative to SN 1991bg and SN 1998de, but still one of the fastest fading Type Ia light curves ever observed. For SN 1998bp (Jha 2002) we directly measure $\Delta m_{15}(B) = 1.78 \pm 0.05$, consistent with the derived stretch parameters.

The observed $B_{max} - V_{max}$ color for SN 1999by is 0.51 ± 0.03 mag. This is extremely red compared to SNe Ia of mid-range decline rates (Phillips et al. 1999), which have $B_{max} - V_{max} < 0.1$. Since the host of SN 1999by is a spiral with obvious dust patches, reddening may explain this color. However, other fast declining SNe Ia appear to be intrinsically red (Leibundgut et al. 1993; Modjaz et al. 2001) near maximum and many of these occurred in elliptical hosts with minimal dust. Figure 7 plots the color curves for SN 1999by compared with other fast-declining events.

Lira (1995) has shown that SNe Ia with low extinction tend to have uniform $B - V$ colors between 30 and 90 days after the time of V-band maximum. This appears to hold for

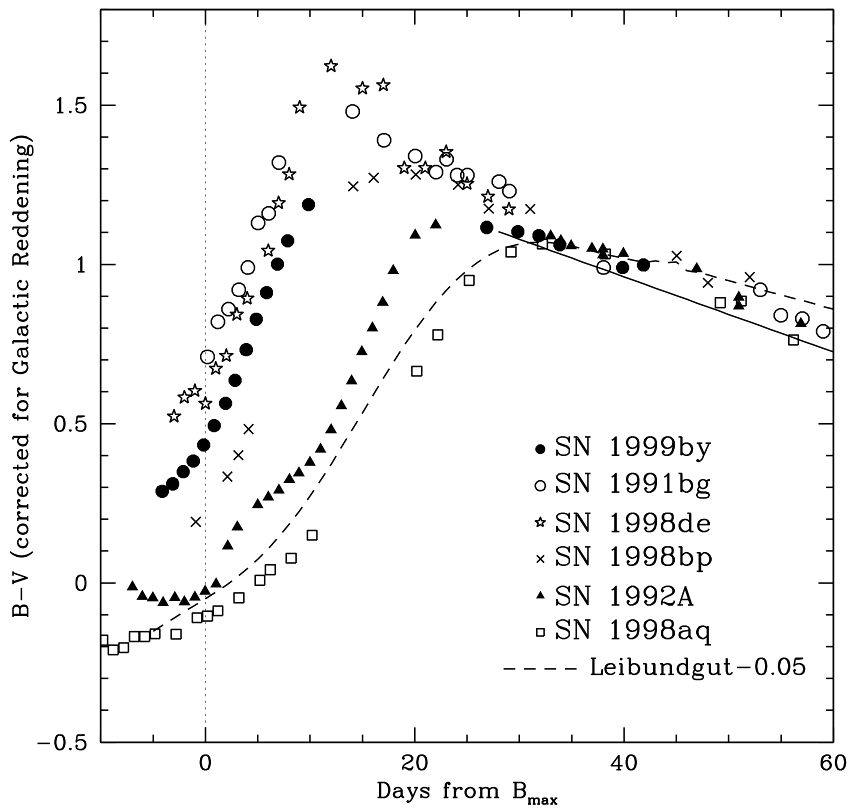

Fig. 7.— $B-V$ color for seven SNIa corrected for Galactic extinction. The solid line is the empirical relation of Lira (1995) for unextinguished supernovae at late-times. The Leibundgut templates have been shifted by 0.05 mag to correct for the average reddening to SNIa from Phillips et al. (1999).

fast decliners as well, although it has been tested with very few events. This fact has been exploited by Phillips et al. (1999) to correct the brightness of a large sample of SNe Ia for dust extinction. The Lira relation,

$$(B-V)_o = 0.725 - 0.0118(\mathrm{T}(V_{max}) - 60) \tag{1}$$

is also plotted in Figure 7. The average difference between the Lira relation and the late-time supernova color is only 0.014±0.020 mag, suggesting that extinction from the host galaxy is minimal and may indicate that the supernova exploded on the near side of the NGC 2841 disk.

Though a combination of our IR photometry and that of Höflich et al. (2002) shows a gap at the time of maximum light, we can fit a polynomial to the H- and K-band data

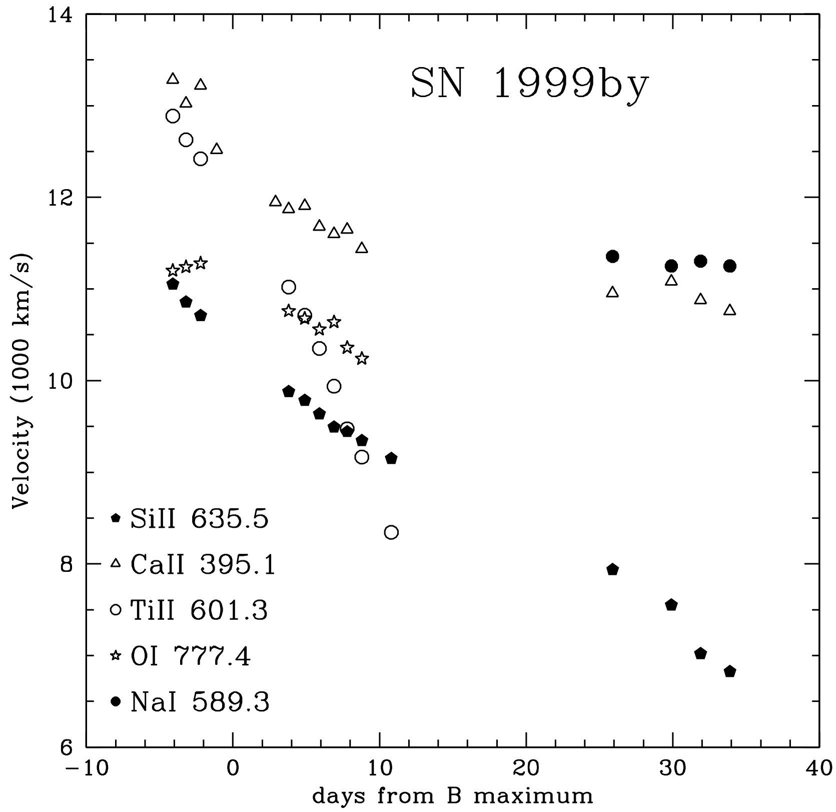

Fig. 8.— Absorption minimum velocities of Si II 635.5 nm, Ca II 395.1 nm, Ti II 601.3 nm, O I 777.4 nm and Na I 589.3 nm lines in SN 1999by.

to derive the maximum magnitudes in those two bands (see Figure 3). We do not feel that the J-band photometry gives us the same option. The H- and K-band maxima occurred about 5 days *after* $\mathrm{T}(B_{max})$. All other known Type Ia supernovae, including the rather fast decliner SN 1986G, have IR maxima that occurred about 3 days *before* $\mathrm{T}(B_{max})$ (Meikle 2000, Krisciunas et al. 2004b).

3.2. The Spectra

The first spectrum was taken 4 days before $\mathrm{T}(B_{max})$ and the data follow the spectral development without a major interruption until 12 days after maximum.

Comparing the spectrum of SN 1999by at maximum light to spectra of SNe Ia of mid-range decline rates, we see the characteristic Si II feature at 635.5 nm is blueshifted to $\approx$

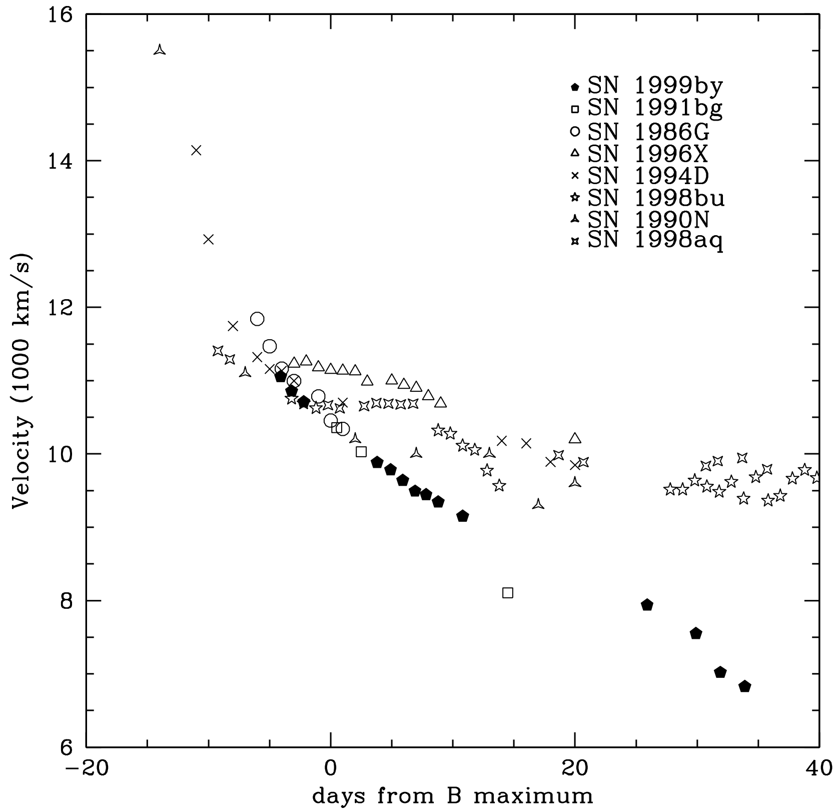

Fig. 9.— Comparison of the Si II 635.5 nm absorption velocity for SN 1999by and other SNIa. While the velocities are similar at maximum, the subluminous supernovae continue to decline in photospheric velocity so at late-times they are distinguishable from more luminous events.

615 nm. There is also a prominent absorption band between 420 nm and 440 nm which is unique to fast-declining SNe Ia. The band as well as absorption at 470 nm and 505 nm were observed in SN 1991bg and have been attributed to Ti II (Filippenko et al. 1992a). The 420 nm band deepens over the observing span but was present even before maximum.

Another feature unique to fast-declining events is the deep O I 777.4 nm line that appears near the edge of the spectral range on most nights. We plot the velocity of O I as measured by the minimum of the absorption trough in Figure 8 along with the velocities derived for other prominent lines such as Si II 635.5 nm, Ca II 395.1 nm and at late times Na I 589.3 nm. The absorption-line velocities have been adjusted for the recession velocity of NGC 2841 and because the photospheric expansion is a significant fraction of the speed of light, a relativistic correction has been applied. Mazzali et al. (1997) found that the O I

line in SN 1991bg remained constant at 11000 km s^{-1} for two weeks after maximum light. In SN 1999by the O I line does decline in velocity from 11200 km s^{-1} before maximum to 10200 km s^{-1} nine days after maximum, which is not as steep as for Si II. This may mean the oxygen shell in SN 1999by is deeper than in SN 1991bg.

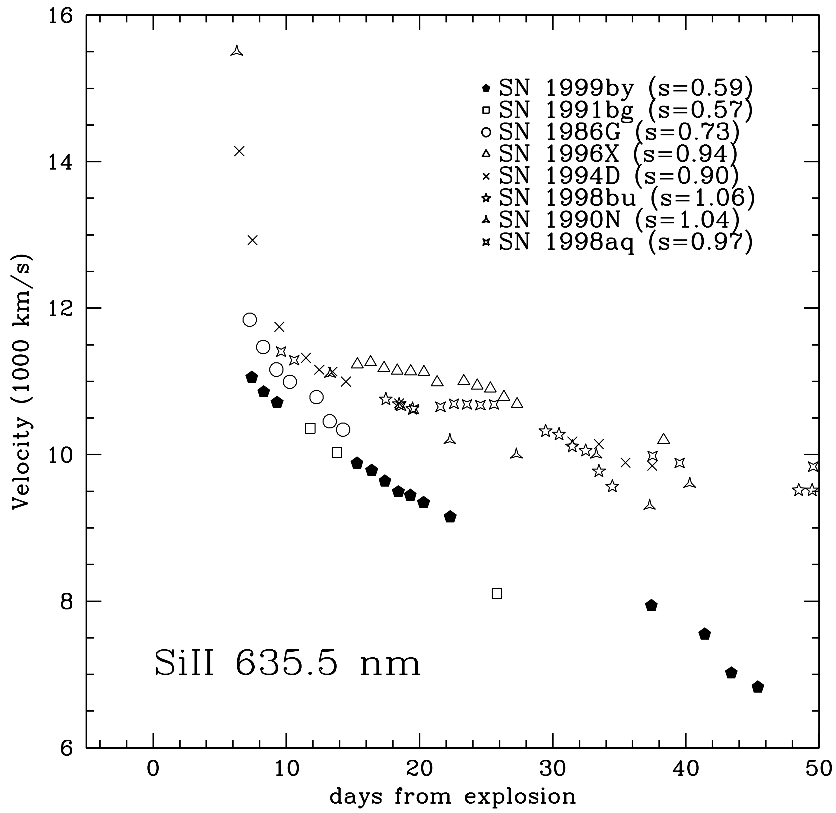

Fig. 10.— Comparison of the Si II 635.5 nm absorption velocity for SN 1999by and other SNIa relative to the time of the explosion. The time of the explosion is estimated from the stretch parameter.

The velocity of the Si II 635.5 nm absorption versus time is compared with a range of other SNe Ia in Figure 9. The velocities of the other SNe were taken from Jha et al. (1999) and Jha (2002). The Si II velocity before maximum light is similar to SNe Ia of mid-range decline rates, but SN 1999by shows a continual drop in velocity like that of SN 1986G, while the typical SN Ia levels off at between 11000 km s^{-1} and 10000 km s^{-1}. A steep decline in velocity was also found by Vinkó et al. (2001) for SN 1999by. We find that the average slope around maximum is 130 km s^{-1}day^{-1} while most so-called normal events have flatter slopes. Only SN 1991bg, with a slope of 160 km s^{-1}d^{-1}, appears to decline faster. Wells et

al. (1994) noted a correlation between $\Delta m_{15}(B)$ and Si II velocity decline rate. These data at least show that Type Ia supernovae with the fastest declining light curves also have the fastest declining Si II velocities after T(B_{max}).

Comparing the spectra of fast-declining SNe Ia with more typical events using the time of B_{max} as the reference is not ideal. It might be better to compare the velocities observed in various supernovae using the time of explosion as the zero point. Riess et al. (1999b) find that for a nominal SN Ia ($\Delta m_{15}(B)$ =1.1) the interval from explosion to T(B_{max}) is 19.5±0.2 days, and this is consistent with SNe Ia observed at high redshift when a stretch correction is applied based on the light curve shape (Goldhaber et al. 2001). It is therefore possible to approximate the day of the explosion as T(exp)=T(B_{max})$-19.5 \times s$, where s is the light curve stretch parameter based on the Leibundgut templates. Since s varies by only about 10 percent for normal luminousity supernovae, this provides only a day or two shift in the relative times for the observed velocities. But in SN 1991bg-like events the time of maximum can correspond to as little as 11 days after explosion. In Figure 10 we plot the observed velocities of the Si II absorption in several supernovae versus the time of explosion estimated as above. When the date of explosion is used as the zero point of the Si II velocities, SN 1999by and SN 1991bg are always lower than normal events. Also, the velocities of intermediate supernovae, such as SN 1986G, fall between the extreme fast-decliners and the normal supernovae. For fast-declining events, there appears to be a simple correlation between the light curve shape and photospheric velocity when measured relative to the time of explosion.

The deep, narrow absorption observed at 567.5 nm in the June spectra (+25 to +35 days) was seen in SN 1991bg and attributed to Na I 589.3 nm by Filippenko et al. (1992b). But models by Mazzali et al. (1997) can not reproduce this feature without adding extra sodium and customizing the distribution to match the small velocity width. If the line is attributed to sodium, then the velocity in SN 1999by is a constant 11300 km s^{-1} compared to 10500 km s^{-1} in SN 1991bg (Turatto et al. 1996) and its width is only 1200 km s^{-1}.

We fit models to the SN 1999by spectra using the parameterized spectral synthesis code SYNOW (Fisher et al. 1999; Hatano et al. 1999a). Figure 11 shows the fit to the May 8 (UT) spectrum taken two days before T(B_{max}). The fit longward of 420 nm is excellent and shows that most of the features come from Si II, Mg II, Ca II, O I and Ti II. We match the absorption feature near 500 nm with Mg I, which has not been identified in a SN Ia before. The fit to the May 17 (+7 d) spectrum (Figure 12) shows the Ti II has increased in strength in the blue and the temperature is low enough to allow neutral calcium to appear in the spectrum.

A great advantage of SYNOW is that the strength of a single ion can be varied to

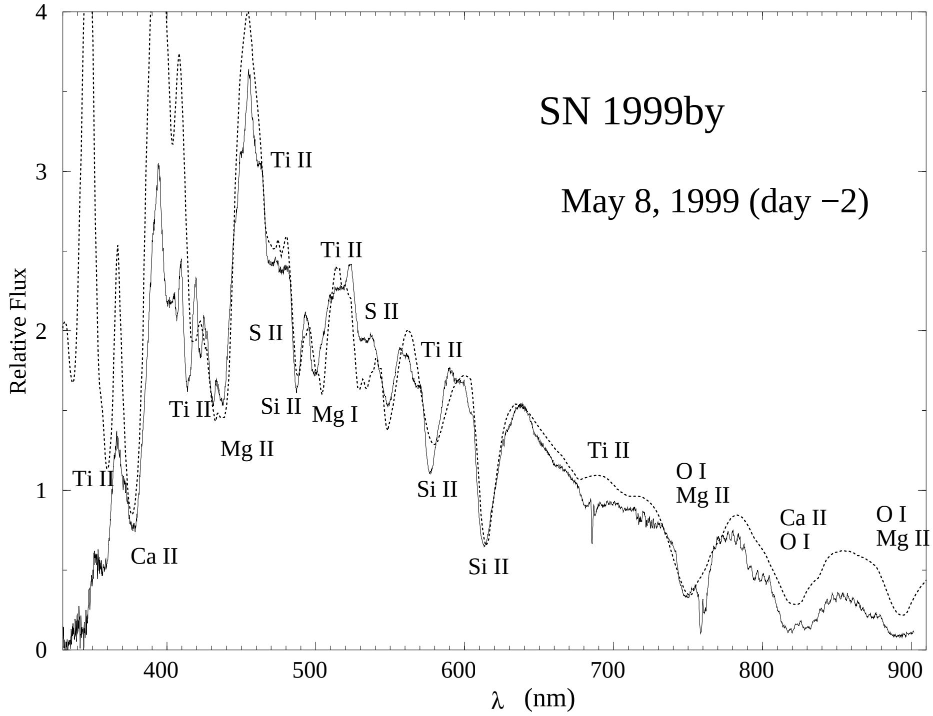

Fig. 11.— A model fit to SN 1999by two days before B_{max}. The solid line is the observed data and the dotted line is the model. Mg I near 500 nm is newly identified in a SNIa.

determine its effect on the entire spectrum. Since Ti II is such an important contributor to the spectra of fast declining SNe Ia, we plot the variation in Ti II optical depth with a fixed Si II optical depth in Figure 13. The continuum temperature is 12000 K for all the models. The blue region of the spectrum, especially the 400-440 nm band is strongly absorbed by the Ti II. Surprisingly, an absorption feature at 580 nm appears at high Ti II optical depths. This has commonly been attributed to Si II (e.g. Filippenko 1997) and, indeed it is dominated by Si II 597.9 nm when the Ti II contribution is small. However at low temperatures a number of Ti II lines take over. This nicely explains the correlation between the 580 nm line depth and $\Delta m_{15}(B)$ found by Nugent et al. (1995). They noted a difficulty in physically accounting for the observed increase of the 580 nm to 615 nm depth ratio with decreasing temperature since the ratio of the two lines should mildly decrease with lowering temperature. This is confirmed in Figure 14 which shows the optical depth ratio $\tau(597.9)/\tau(634.7)$ versus temperature from the study of line strengths in supernova atmospheres by Hatano et al. (1999b). The optical depth ratio of the representative Ti II 601.3 nm to Si II 634.7 nm line is also shown and demonstrates a very rapid increase with a small temperature drop. We conclude that the 580 nm depth to 615 nm depth ratio, called $\mathcal{R}$(Si II) by Nugent et al. (1995) is dominated by

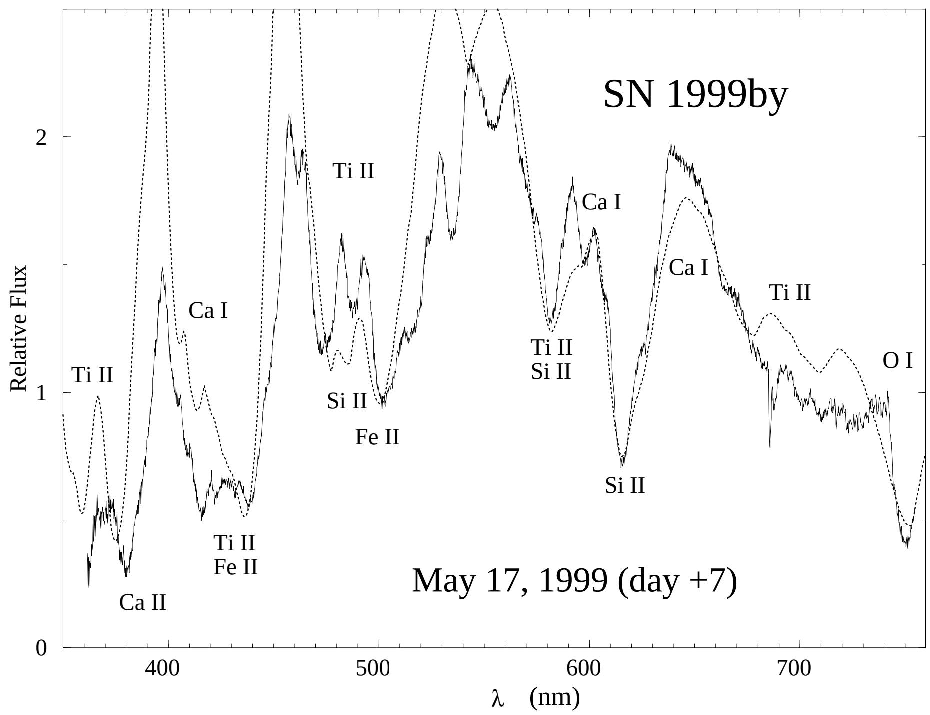

Fig. 12.— A model fit to the observed spectrum of SN 1999by at seven days after B_{max}. The solid line is the observed data and the dotted line is the model. Ca I is identified at a number of locations in this early nebular phase spectrum.

Si II at high temperatures and Ti II at low temperatures. The rise of the Ti II lines appears to be very rapid as the optical depth relative to Si II increases exponentially with decreasing temperature. This suggests that the so-called "peculiar" SNe Ia may represent a rather small deviation from normal events but with a rapid line blanketing by Ti II contributing to the red color, the fast B-band decline, the faint B-band luminosity and the unusual spectral characteristics. The key physical parameter controlling the photospheric temperature may be the ^{56}Ni yield. SNe Ia are generally considered explosions of CO white dwarfs which have reached the Chandrasekhar limit from the transfer of mass from a nearby donor star. Contardo, Leibundgut, & Vacca (2000) found that the ^{56}Ni yield of SN 1991bg was 8 times less than the brightest object in their sample, SN 1992bc.

The 580/615 nm line depth ratio, which we will now call $\mathcal{R}$(Ti II/Si II), should still be a useful indicator of decline rate (and intrinsic brightness), at least for the low temperature events. In Figure 15 we plot $\mathcal{R}$(Ti II/Si II) for supernovae with a wide range of the $\Delta m_{15}(B)$ parameter, restricting the spectra to within three days of B_{max}. We expect the ratio to be relatively flat with temperature when the 580 nm feature is dominated by Si II and begins

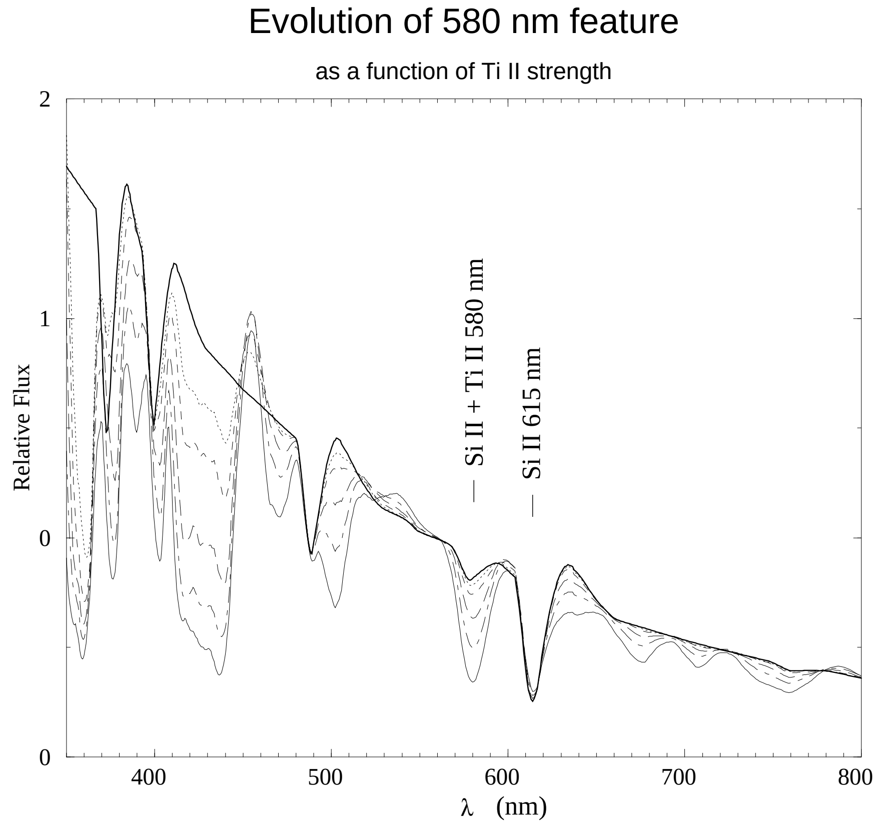

Fig. 13.— A SYNOW model showing only lines of Si II and Ti II on a 12000 K continuum. The thick solid line shows the Si II absorption spectrum with no contribution from Ti II. The thin lines show how the spectrum is modified by varying the optical depth of Ti II. Note the feature at 580 nm, which is normally dominated by Si II, has a large contribution from Ti II when the Ti II abundance is significant.

to increase when Ti II is present. The rise appears to begin for $\Delta m_{15}(B) > 1.2$, so Ti II is present in the red end of the spectrum even in more slowly declining, but otherwise normal SNe Ia. The strong Ti II bands in the blue are probably not apparent for $1.2 < \Delta m_{15}(B) < 1.7$ because the continuum optical depth is much higher there than in the red, but more detailed modelling of this effect is required to confirm this conjecture.

4. Comparison with other SNe Ia: What do we mean by "peculiar"?

4.1. Color

So-called "peculiar" SNe Ia with fast-declining light curves are defined spectroscopically by the presence of strong Ti II absorption (Branch, Fisher, & Nugent 1993). But we have shown that Ti II is detectable for $\Delta m_{15}(B) > 1.2$, and its strength continuously increases

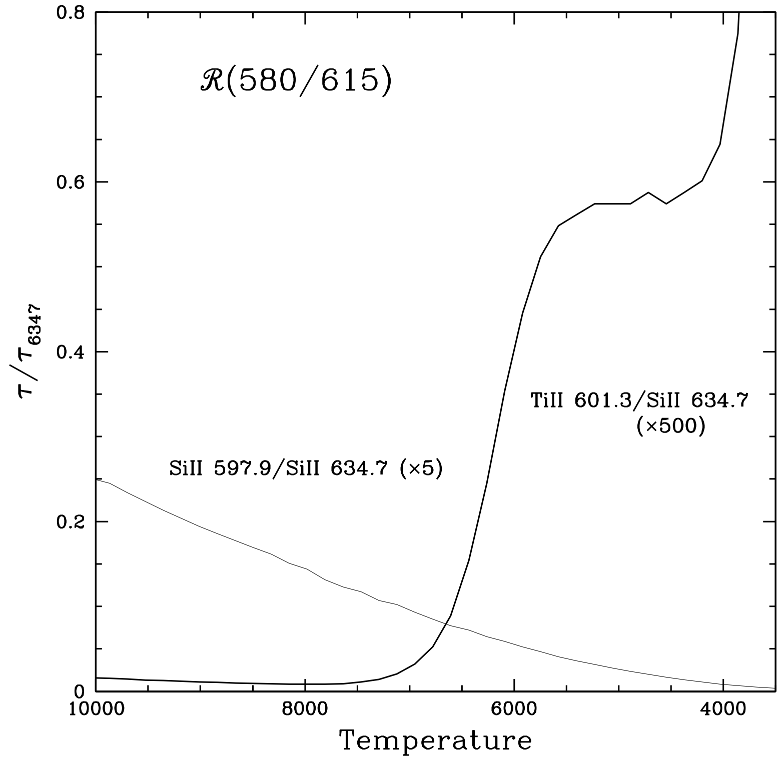

Fig. 14.— Ratio of the optical depth of the Si II line 597.9 nm and Ti II line 601.3 nm to the optical depth of Si II 634.7 nm for a range of temperatures. The optical depths have been multipled to approximate the observed 580/615 depth ratio. The Si II 597.9 strength is expected to decline relative to Si II 634.7 with decreasing temperature while Ti II begins an exponential rise at 7000 K.

between the so-called "normal" events and the extreme SN 1991bg-like objects. The color of the supernova at maximum may be the best discriminator. Phillips et al. (1999) has shown that the intrinsic $B_{max} - V_{max}$ color of SNe Ia is less than 0.1 for $\Delta m_{15}(B) < 1.7$. A compilation of fast-declining SNe Ia is given in Table 6 for events with $\Delta m_{15}(B) \geq 1.69$. We have left out SN 1992br ($\Delta m_{15}(B)$=1.69; Hamuy et al. 1996b) and SN 1996bk ($\Delta m_{15}(B)$=1.75; Riess et al. 1999a) because their light curves are poorly defined. SN 1992K was not discovered until an estimated 12 days after maximum and its parameters are poorly determined but we include it here because it is well established in the literature. The $B_{max} - V_{max}$ color versus $\Delta m_{15}(B)$ for the objects with fast light curves is shown in Figure 16 and demonstrates a sharp break near $\Delta m_{15}(B) \sim 1.7$. Despite the rapid change in slope, the fast-declining events connect well to the end of the "normal" color distribution. No events with $\Delta m_{15}(B) > 1.7$ have been found with blue colors, so there remains a monotonic, single-valued function connecting light curve shape and color.

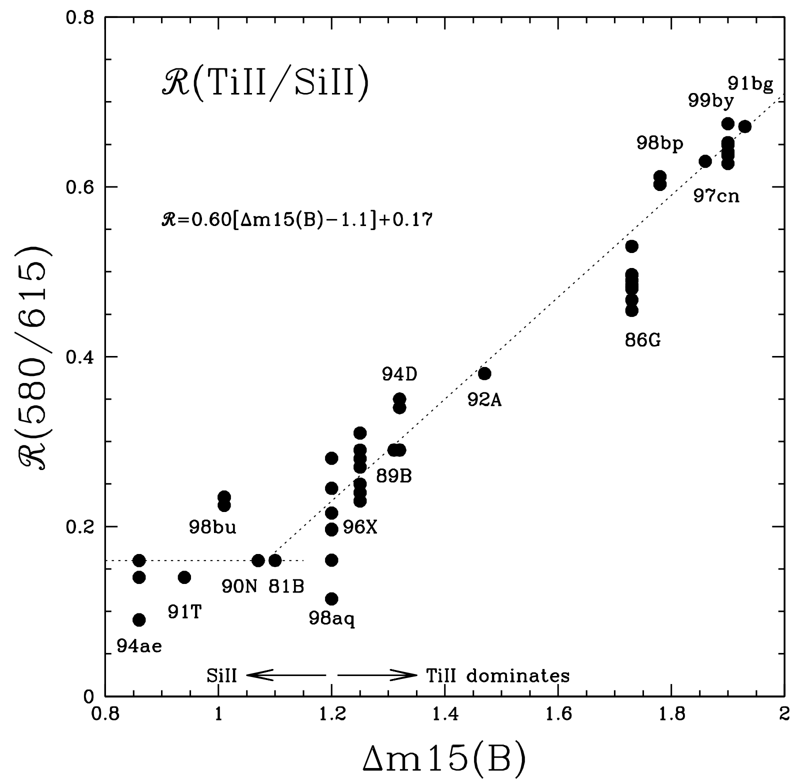

Fig. 15.— Ratio of 580 nm to 615 nm line depth for 15 supernovae. Each point represents an individual spectrum and the data is restricted to ±3 days from B_{max}. The fit applies to supernovae with $\Delta m_{15}(B) > 1.2$. For $\Delta m_{15}(B) < 1.2$ the line ratio is dominated by Si II and is expected to be nearly constant, making the ratio a poor indicator of luminosity, decline rate or temperature.

4.2. Luminosity

Several "peculiar" events listed in Table 6 are distant enough to be in the Hubble flow so their luminosities can be compared with so-called normal SNe Ia. Figure 17 shows the absolute magnitudes derived for the fast decliners vs. $\Delta m_{15}(B)$, assuming $H_0 = 72$ km s^{-1} Mpc^{-1} (Freedman et al. 2001). The photometric error bars include an uncertainty of 400 km s^{-1} in the recession velocity due to the unknown peculiar velocities of the hosts. SN 1999by is included by using the Cepheid distance of 14.1±1.5 Mpc to NGC 2841 from Macri et al. (2001). The SNe Ia with smaller decline rates are from Phillips et al. (1999) and all magnitudes have been corrected using the reddening estimates from that work. The B-band luminosities show a steep decline toward high $\Delta m_{15}(B)$ which is not well fit by an extension of the Phillips et al. (1999) quadratic fit. Instead, we use an exponential function to match decline rate with luminosity. The best fits for B, V and I are

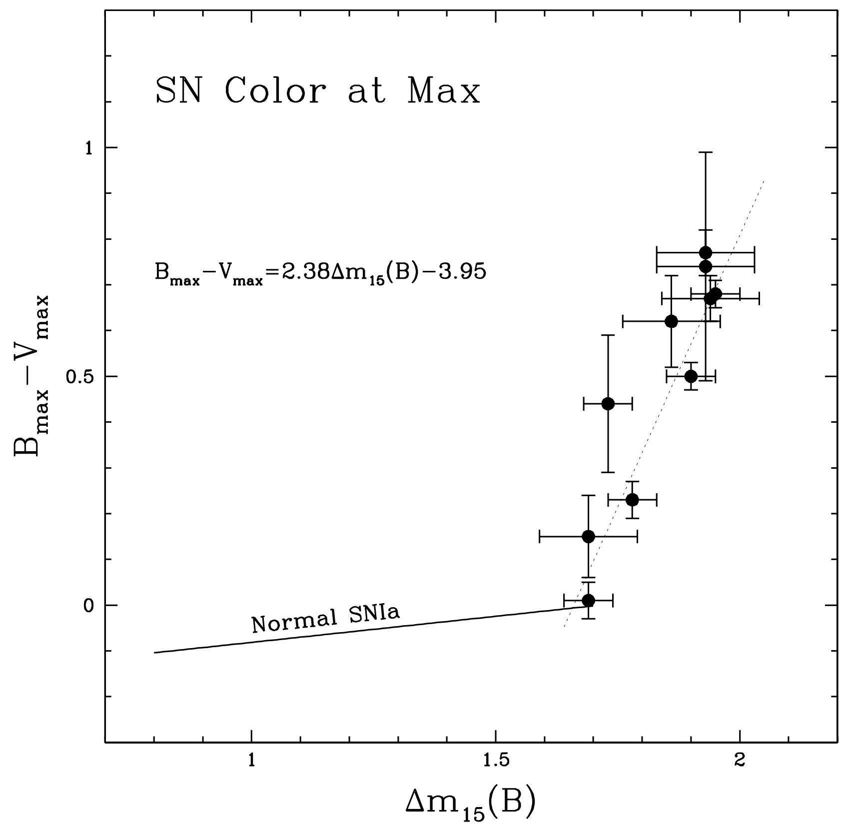

Fig. 16.— The $B_{max} - V_{max}$ color for SNIa. The solid line shows the color derived by Phillips et al. (1999) for normal SNIa. The dotted line is the weighted linear fit to the supernovae listed in Table 6.

$$M(B) = -19.338 + 5\text{Log}(H_0/72) + 0.139 \left(\exp[3.441\ (\Delta m_{15}(B) - 1.1)] - 1\right) \quad (2)$$

$$M(V) = -19.328 + 5\text{Log}(H_0/72) + 0.096 \left(\exp[3.450\ (\Delta m_{15}(B) - 1.1)] - 1\right) \quad (3)$$

$$M(I) = -18.817 + 5\text{Log}(H_0/72) + 0.060 \left(\exp[3.402\ (\Delta m_{15}(B) - 1.1)] - 1\right) \quad (4)$$

using a χ^2 minimization with three free parameters. Adding an additional linear slope parameter did not improve the overall fit which has an rms scatter of 0.19 mag in each band. While this is a larger scatter than obtained when fitting SNe Ia restricted to $\Delta m_{15}(B) < 1.7$, it shows that so-called "normal" and "peculiar" SNe Ia can be calibrated in a uniform manner, which argues for their common origin.

However, while there is evidence that the absolute magnitudes in the $UBVRI$ bands present a monotonic sequence, SN 1999by is unusual regarding its IR maxima. Krisciunas,

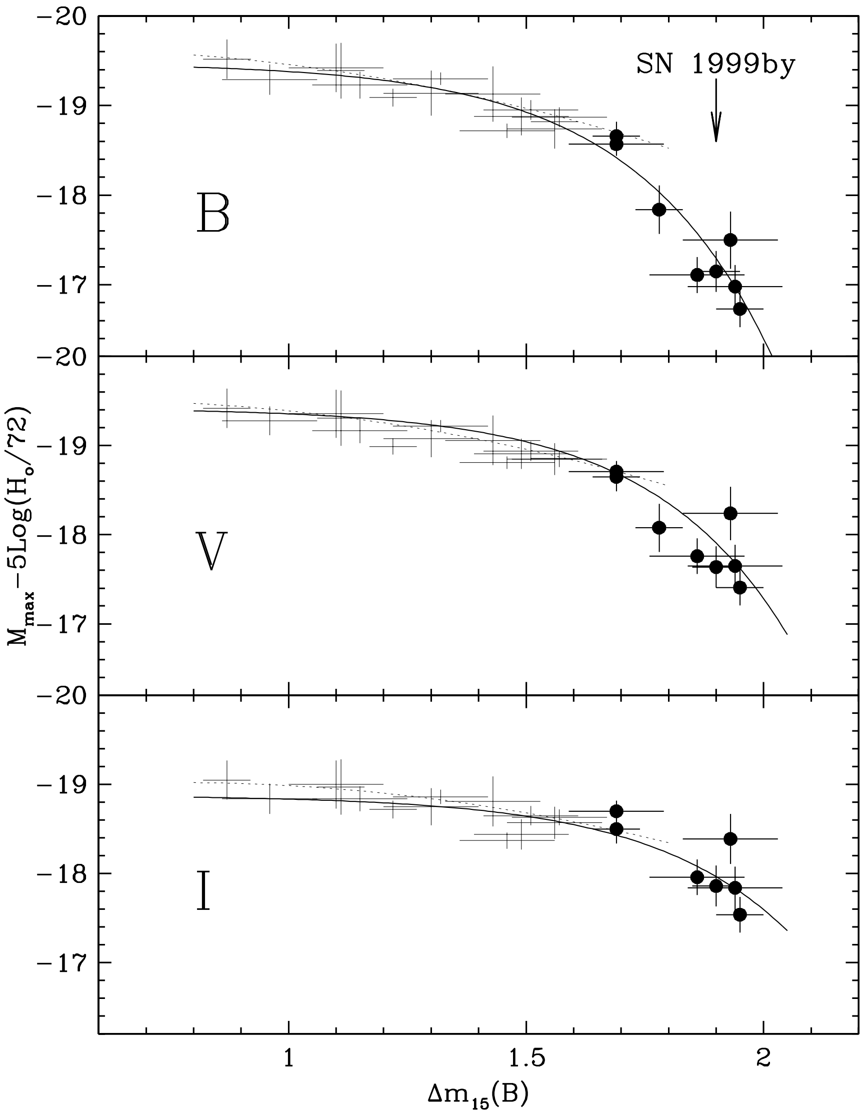

Fig. 17.— The absolute magnitudes of SNe Ia versus $\Delta m_{15}(B)$ from Phillips et al. (1999), with so-called "peculiar" supernovae added (solid points). The dotted line is the quadratic fit derived by Phillips et al. for $\Delta m_{15}(B) < 1.7$. The solid line is an exponential fit which attempts to fit all the objects represented.

Phillips, & Suntzeff (2004a) show that SNe Ia appear to have JHK absolute magnitudes at maximum which are independent of the decline rate parameter, at least for the range of $0.8 \lesssim \Delta m_{15}(B) \lesssim 1.7$. We obtain $M_H(\max) = -17.87 \pm 0.24$ and $M_K(\max) = -17.79 \pm 0.25$. These are to be compared with the mean values of −18.25 and −18.42, respectively, for the objects analyzed by Krisciunas et al. (2004a). SN 1999by is $\Delta H = 0.38 \pm 0.24$ and $\Delta K = 0.63 \pm 0.25$ mag fainter than the mean absolute magnitudes of the slower decliners. While both of these values are less than 3-σ outliers, it is noteworthy that SN 1999by has

the faintest IR absolute magnitudes at maximum yet found for SNe Ia. It could be that the fast-declining SNe Ia have statistically different absolute magnitudes at maximum in the IR compared to other SNe Ia.

5. Two for One: SN 1957A

The rather prolific galaxy NGC 2841 has also hosted SN 1957A, which was identified as a subluminous Type I supernova by Branch & Doggett (1985). Branch, Fisher, & Nugent (1993) describe it as a SN 1991bg-like event and a reanalysis of its photographic spectra by Casebeer et al. (2000) shows a flux deficit around 420 nm relative to "normal' SNe Ia at a similar age, which suggests the presence of Ti II. However, in the blue part of the spectrum a Type Ic supernova can be mistaken for subluminous SN Ia after maximum, so SN 1957A can not be classified as a Type Ia with absolute certainty. Still, we can analyze the historical light curve compiled by Leibundgut et al. (1991) as if it was a Type Ia.

We fit the blue photographic light curve by stretching the Leibundgut template and find that maximum light occurred on Julian Day 2,435,901±2 at $m_{pg} = 14.43 \pm 0.2$. The best fit stretch parameter is 0.54±0.03 corresponding to a $\Delta m_{15}(B) = 2.00 \pm 0.07$. The V-band light curve is not as well sampled, so we use the same stretch factor and time of maximum to find a $V_{max} = 13.63 \pm 0.2$. The color of SN 1957A between 30 and 90 days from maximum is not very well determined given the errors on faint photographic magnitudes, but we will assume minimal extinction from the host. We convert between standard B-band and m_{pg} using equation 31 from Pierce & Jacoby (1995) and find SN 1957A was 0.88 mag fainter than SN 1999by in B and 0.48 mag fainter in V. If SN 1957A was truly an unreddened SN Ia, then it was the faintest yet observed with $M_B = -16.3 \pm 0.2$ and $M_V = -17.2 \pm 0.2$. These are consistent with the luminosities predicted by equations 2 and 3 for $\Delta m_{15}(B) = 2.00$ of $M_B = -16.40$ and $M_V = -17.28$. The intrinsic color we find from the light curves of SN 1957A is $B_{max} - V_{max} = 0.87$ which is close to the 0.81 mag expected from its decline rate (see Figure 16).

6. The Hubble Constant

The measurement of a Cepheid distance to NGC 2841 provides an opportunity to make an independent estimate of the Hubble parameter using fast-declining SNe Ia alone. Jha et al. (1999) noted that most of the SNe Ia calibrated with Cepheids have slow light curve decline rates. If there is a systematic bias caused by this selection, then the Hubble

parameter estimated from fast decliners may be significantly different from the Key Project value (Freedman et al. 2001). However, with only one directly calibrated fast decliner the uncertainty on the derived Hubble parameter can be no better than 10 percent.

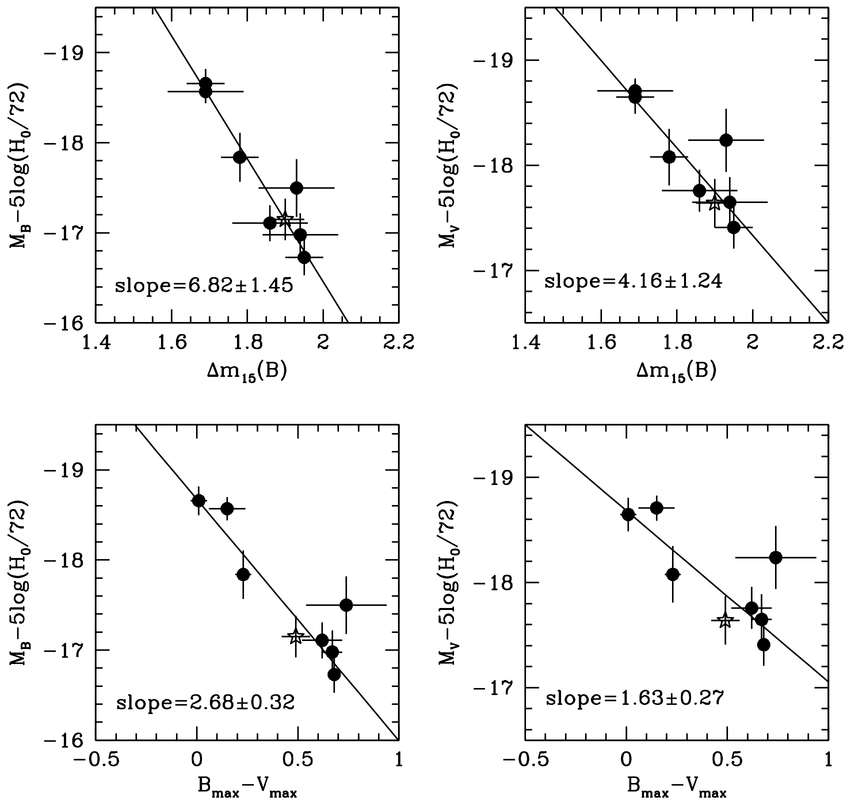

Fig. 18.— The absolute magnitudes of fast-declining SNe Ia versus $\Delta m_{15}(B)$ and $B_{max} - V_{max}$. The star indicates the values for SN 1999by although it is not used in the linear fit.

There are seven SNe Ia listed in Table 6 that can be considered in the Hubble flow, i.e. with recession velocities in excess of 3000 km s^{-1}. We plot the luminosities of these in Figure 18 (assuming $H_0 = 72$ km s^{-1} Mpc^{-1}) as a function of $\Delta m_{15}(B)$. We also plot the luminosities versus $B_{max} - V_{max}$ because it appears to be highly correlated with the light curve shape in the fast decliners. The slope of the linear fit to the points (excluding SN 1999by) is then used to estimate a magnitude correction to the fiducial values $\Delta m_{15}(B)$=1.90 and $B_{max} - V_{max} = 0.49$ (extinction corrected). SN 1992K is consistently the most discrepant point from the linear trend and its errors in decline rate and peak brightness may be underestimated.

Using the method described in Jha et al. (1999), we derive a Hubble constant of $H_0 = 75^{+12}_{-11}$ km s^{-1} Mpc^{-1} applying the $\Delta m_{15}(B)$ parameter to correct the seven events to

SN 1999by. Using $B_{max} - V_{max}$ as the luminosity indicator, we find $H_0 = 84^{+12}_{-11}$ km s^{-1} Mpc^{-1}. These are consistent with the Key Project value derived from normal SNe Ia (Freedman et al. 2001) and suggest that no systematic error in the Hubble constant is being introduced by ignoring low luminosity events.

7. Conclusions

We present well-sampled $UBVRI$ light curves of SN 1999by and the evolution of the spectra over a period of 40 days around maximum. We estimate a light curve parameter $\Delta m_{15}(B)$=1.90±0.05 mag which is one of the fastest observed decline rates for a SN Ia. The observed color at maximum $B_{max} - V_{max} = 0.51$ mag, which is red for a SN Ia, but the late-time $B - V$ color suggests little dust extinction along the line-of-sight. From the recent Cepheid distance to the host galaxy (Macri et al. 2001) and the assumption of minimal host extinction, we find the absolute brightness at maximum to be $M_B = -17.15 \pm 0.23$ and $M_V = -17.64 \pm 0.23$.

To date SN 1999by has the faintest absolute magnitudes at maximum in the near-IR of any known Type Ia supernova. Whether SN 1999by is a statistical outlier or this facet is representative of other fast decliners is not yet known. While most SNe Ia may be considered IR standard candles (Meikle 2000, Krisciunas et al. 2004a), the objects with $\Delta m_{15}(B) \gtrsim 1.7$ might be subluminous.

Comparing SN 1999by with other so-called "peculiar" SNe Ia, we find that it had a slower decline rate and was not as red at maximum as SN 1991bg or SN 1998de. It was slightly more luminous than SN 1998de, but fainter than SN 1998bp. There appears to be an excellent correlation between luminosity, decline rate and color for these subluminous objects and these observables blend smoothly into the luminous population of SNe Ia. We show that any SN Ia with a decline rate of $\Delta m_{15}(B) < 2.0$ can be used as a distance indicator, although the scatter increases with large $\Delta m_{15}(B)$ due to the steep correction curve and poor calibration at the faint end of the population. We test this by using the fast decliners to estimate the Hubble constant and find it consistent with the value found from the "normal" population.

We find that the 580 nm feature commonly associated with Si II and correlated with luminosity is actually dominated by Ti II for the SN 1991bg-like events and is likely to have a significant Ti II component even for more standard SNe Ia. This means that the depth ratio of 580 nm to 615 nm should not be used as a luminosity indicator for $\Delta m_{15}(B) < 1.2$, but it still makes an excellent temperature and luminosity estimator for supernovae with

faster than normal light curves. Predictions of the Ti II strength with temperature suggest that Ti II optical depth increases rapidly over a small range of temperature. It is this non-linear effect that makes SN 1991bg-like events appear so odd when compared to more typical SNe Ia which change their character little over a wide temperature span. We conclude that SN 1991bg-like supernovae should not be considered as "peculiar" SNe Ia since along with "Branch normal" events they form a continuous, smooth, and single-valued distribution of luminosity, color, Ti II strength, and perhaps even ^{56}Ni yield.

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Table 1. Local Standard Star Magnitudes

Star	U	B	V	R	I	n[a]
1	14.642	14.262	13.503	13.059	12.656	3
2	15.490	14.999	14.185	13.725	13.312	4
3	16.131	16.191	15.708	15.407	15.088	6
4	17.748	17.335	16.530	16.049	15.583	6
5	16.948	16.182	15.269	14.713	14.209	2
6	16.842	15.713	14.650	13.994	13.501	2
7	18.630	18.332	17.575	17.127	16.701	6
8	18.931	18.207	17.314	16.798	16.298	6
9	18.333	18.101	17.363	16.904	16.472	6
10	18.598	17.946	17.049	16.488	16.085	4

[a]Number of nights calibrated.

Table 2. *UBVRI* Photometry of SN 1999by[a]

JD[b]	U	B	V	R	I	Observer
1304.67	13.96 (02)	13.95 (02)	13.64 (02)	13.49 (02)	13.40 (02)	Caldwell
1305.68	13.89 (02)	13.81 (02)	13.49 (02)	13.33 (02)	13.26 (02)	Caldwell
1306.67	13.84 (02)	13.74 (02)	13.37 (02)	13.20 (02)	13.14 (02)	Rines
1307.64	13.82 (02)	13.67 (02)	13.27 (02)	13.09 (02)	13.05 (02)	Rines
1308.63	13.84 (02)	13.66 (02)	13.21 (02)	13.02 (02)	12.99 (02)	Rines
1309.63	13.89 (02)	13.68 (02)	13.17 (02)	12.97 (02)	12.94 (02)	Rines
1310.73	13.99 (02)	13.72 (02)	13.14 (02)	12.94 (02)	12.91 (02)	McIntosh
1311.64	14.12 (03)	13.80 (02)	13.14 (02)	12.93 (02)	12.91 (02)	McIntosh
1312.70	14.30 (03)	13.92 (02)	13.17 (02)	12.95 (02)	12.90 (02)	Garnavich
1313.66	14.46 (03)	14.07 (02)	13.23 (02)	12.98 (02)	12.93 (02)	Dendy
1314.65	14.67 (03)	14.24 (02)	13.31 (02)	13.03 (02)	12.95 (02)	Dendy
1315.68	14.84 (03)	14.43 (02)	13.42 (02)	13.10 (02)	12.99 (02)	Dendy
1316.65	15.06 (04)	14.61 (02)	13.52 (02)	13.17 (02)	13.01 (02)	Pahre
1318.65	15.38 (05)	14.97 (02)	13.76 (02)	13.33 (02)	13.08 (02)	Pahre
1335.69	16.50 (07)	16.21 (03)	15.08 (03)	14.65 (03)	14.19 (03)	Szentgyorgyi
1338.66	16.57 (07)	16.33 (03)	15.21 (03)	14.81 (03)	14.36 (03)	Szentgyorgyi
1340.66	16.63 (07)	16.40 (03)	15.29 (03)	14.93 (03)	14.48 (03)	Szentgyorgyi
1342.67	16.71 (10)	16.45 (05)	15.37 (05)	15.03 (06)	14.59 (06)	Szentgyorgyi
1348.66	16.68 (15)	16.60 (08)	15.59 (06)	15.35 (09)	14.91 (09)	Falco
1350.65	16.77 (07)	16.66 (04)	15.65 (03)	15.42 (04)	15.00 (04)	Falco
1487.97	20.67 (30)	19.72 (05)	19.62 (05)	19.61 (05)	18.80 (05)	Stanek
1521.99	···	20.39 (20)	20.17 (12)	20.38 (20)	19.45 (30)	Garnavich

[a]The values in parentheses are the uncertainties in hundredths of a magnitude.

[b]Julian Date − 2,450,000.

Table 3. Infrared Photometry of SN 1999by

JD[a]	J	H	K	Observer
1299.80	···	14.65 (0.09)	···	Tustin
1301.63	14.16 (0.05)	14.16 (0.09)	14.20 (0.08)	Vaisanen
1303.63	13.44 (0.03)	13.33 (0.07)	···	Vaisanen
1320.71	13.68 (0.03)	13.02 (0.03)	13.21 (0.04)	Pahre
1322.71	13.71 (0.03)	13.18 (0.04)	13.25 (0.05)	Pahre
1324.64	13.82 (0.03)	13.33 (0.04)	13.31 (0.04)	Kenyon
1326.63	13.87 (0.03)	13.51 (0.07)	13.68 (0.07)	Kenyon
1327.67	14.01 (0.04)	13.61 (0.07)	13.78 (0.05)	Garnavich
1328.64	14.20 (0.05)	13.74 (0.08)	13.72 (0.08)	Garnavich
1330.67	14.23 (0.05)	14.07 (0.08)	14.12 (0.08)	Megeath
1360.64	···	15.74 (0.17)	···	Mader

[a]Julian Date − 2,450,000.

Table 4. Log of Spectroscopic Observations

UT Date[a]	JD[b]	Coverage (nm)	Exposure Time (s)	Observer
May 6	1304.72	362-754	3×300	Berlind
May 7	1305.63	362-754	2×660	Calkins
May 8	1306.64	327-901	2×480	Calkins
May 9	1307.64	362-560	600	Dendy
May 13	1311.67	362-560	600	Dendy
May 14	1312.64	327-940	3×480	Berlind
May 15	1313.65	362-754	2×360	Berlind
May 16	1314.67	362-754	2×420	Berlind
May 17	1315.66	362-754	3×300	Garnavich
May 18	1316.63	362-754	3×420	Garnavich
May 19	1317.63	362-754	3×480	Garnavich
May 21	1319.64	500-750	2×600	Calkins
May 22	1320.64	390-595	2×600	Calkins
Jun 5	1334.66	362-754	2×600	Calkins
Jun 9	1338.66	362-754	2×600	Berlind
Jun 11	1340.65	362-754	900	Calkins
Jun 13	1342.65	362-754	900	Calkins
Jun 22	1351.65	362-754	900	Calkins

[a]Year = 1999.

[a]Julian Date − 2,450,000.

Table 5. Light Curve Parameters at Maximum Light

Band	JD_{max}[a]	Maximum magnitude[b]
U	1307.6 (0.3)	13.82 (0.03)
B	1308.8 (0.3)	13.66 (0.02)
V	1310.8 (0.4)	13.15 (0.02)
R	1311.4 (0.4)	12.94 (0.02)
I	1311.8 (0.5)	12.91 (0.03)
H	1314.0 (2.0)	12.89 (0.04)
K	1313.5 (2.0)	12.96 (0.09)

[a]Julian Date − 2,450,000.

[b]These are observed values, uncorrected for extinction along the line of sight.

Table 6. SN Ia with Fast-Declining Light Curves[a]

SN	$\Delta m_{15}(B)$	cz	B_0(max)	V_0(max)	I_0(max)	Reference
1992bo	1.69 (05)	5445[b]	15.73 (07)	15.75 (06)	15.90 (05)	Hamuy et al. (1996)
1993H	1.69 (10)	7447[b]	16.51 (08)	16.37 (05)	16.38 (06)	Hamuy et al. (1996)
1986G	1.73 (07)	547	9.90 (30)	9.46 (30)	⋯	Phillips et al. (1987; 1999)
1998bp	1.78 (05)	3127[b]	15.29 (07)	15.06 (05)	⋯	Jha et al. (2001)
1997cn	1.86 (10)	5246[b]	17.20 (10)	16.55 (10)	16.35 (10)	Turatto et al. (1998)
1999by	1.90 (05)	638	13.59 (03)	13.10 (03)	12.88 (03)	This work
1992K	1.93 (10)	3334[b]	15.83 (21)	15.09 (16)	14.94 (15)	Hamuy et al. (1996)
1991bg	1.93 (05)	1060	14.58 (05)	13.82 (03)	13.50 (05)	Leibundgut et al. (1993)
1999da	1.94 (10)	3748[b]	16.60 (06)	15.93 (06)	15.74 (04)	Krisciunas et al. (2001)
1998de	1.95 (05)	4625[b]	17.31 (04)	16.63 (04)	16.50 (05)	Modjaz et al. (2001)
1957A[c]	2.00 (07)	638	14.47 (20)	13.58 (20)	⋯	This work

[a]Radial velocities given in column 3 are measures in km s^{-1}. Magnitudes in columns 4, 5, and 6 are corrected for extinction along the line of sight.

[b]Corrected to CMB frame.

[c]Probable Type Ia supernova.